Hydrogen-Deficient Stars
ASP Conference Series, Vol. xxx, 2008
Werner & Rauch

Hot DQ White Dwarf Stars: A New Challenge to Stellar Evolution

P. Dufour[1], J. Liebert[1], G. Fontaine[2], N. Behara[3]

[1]*Department of Astronomy and Steward Observatory, University of Arizona, 933 North Cherry Avenue, Tucson, AZ 85721*
[2]*Département de Physique, Université de Montréal, CP6128, Succ. Centre-Ville, Montréal, QC H3C 3J7, Canada*
[3]*CIFIST, GEPI, Observatoire de Paris-Meudon, 92195, France*

Abstract.
We report the discovery of a new class of hydrogen-deficient stars: white dwarfs with an atmosphere primarily composed of carbon, with little or no trace of hydrogen or helium. Our analysis shows that the atmospheric parameters found for these stars do not fit satisfactorily in any of the currently known theories of post-asymptotic giant branch (AGB) evolution, although these objects might be the cooler counter-part of the unique and extensively studied PG 1159 star H1504+65. These stars, together with H1504+65, might thus form a new evolutionary post-AGB sequence.

1. Introduction

Canonical stellar evolution predicts that the majority of white dwarfs have a core made of carbon and oxygen which itself is surrounded by a helium layer and also, for ~ 80 % of known white dwarfs, by an additional hydrogen layer. Thus, all white dwarfs have been traditionally found to belong to one of these two categories: those with a hydrogen-rich atmosphere (the DAs) and those with a helium-rich atmosphere (the non-DAs). The latter are believed to be the result of a late He-shell flash (Herwig et al. 1999) at the end of the post-AGB phase (the so-called born-again scenario) which almost completely removes hydrogen and mixes interior material (mostly carbon and oxygen) with the helium envelope. With cooling, because of gravitational settling, helium gradually diffuses upward and the stars then appear as helium-rich white dwarfs (spectral type DO for $T_{\rm eff} >\sim 40,000$ K and DB below that). When these white dwarfs cool to approximately 13,000 K, carbon makes one final appearance as it is convectively dredged-up from the diffusion tale by the deep superficial helium convection zone (DQ spectral type, Pelletier et al. 1986). Evolutionary models (Fontaine & Brassard 2005) predict that the carbon abundance reaches a maximum at $\sim 10,000$ K and decreases monotonically with decreasing effective temperature (note that even at maximum contamination, helium always remains the dominant constituent of the atmosphere with log C/He ~ -3).

Detailed model atmosphere analysis of DQ white dwarfs (Dufour et al. 2005) have confirmed the theory on the cool side of the maximum contamination but very little has been done to test the theory on the hot ascending side

of the curve. The reason for this is simple: only two objects (G227-5 and G35-26, Wegner & Koester 1985; Thejll et al. 1990) were known to exhibit traces of carbon in the optical in that temperature regime. Fortunately, the situation has recently changed drastically thanks to the discovery of several new hot white dwarfs with carbon lines in the Sloan Digital Sky Survey (Liebert et al. 2003). However, appropriate atmospheric models were not available at the time, so a detailed analysis of these stars could not be undertaken. We have thus recently developed the appropriate atmospheric models and performed the analysis of these objects.

2. Spectroscopic and photometric analysis of hot DQ stars

Most stars in our sample are very similar to the previously known DQ stars G227-5 and G35-26 and exhibited mostly C I lines. However, a few showed a more complex and rich spectrum that is attributed to C II absorption lines. While the former were relatively easy to model (results will be presented elsewhere), it became rapidly obvious that the latter could not be modeled by simply increasing the effective temperature. Indeed, in such cases, helium is no longer spectroscopically invisible and strong HeI lines (λ4471 in particular) are expected. We soon came to the stunning conclusion that no combination of carbon and helium could successfully reproduce the observed features by assuming a helium-dominated atmophere. We instead find that a good fit to both the spectra and energy distribution is possible only by considering an atmophere made primarily of carbon, with little or no trace of hydrogen and helium !! We found 8 such objects in the SDSS DR4 archive, 6 of which are presented in figure 1. Since the signal-to-noise ratio of the SDSS spectra is rather poor, only crude upper limits (except for two that show explicitly Hα and Hβ) can be obtained for the hydrogen and helium abundances (higher quality data should be secured shortly).

3. H1504+65 and evolutionay scenarios

How are these stars formed ? The most attractive scenario is that these are the progenies of objects such as the unique hot PG1159 star H1504+65 (Werner 1991; Werner & Wolff 1999; Werner et al. 2004). The latter is the only other known star not showing any trace of hydrogen and helium in its spectra and has a very unusual composition with $\sim$ 50% C and $\sim$ 50% O. Although the exact reason for the He-deficiency is still not fully understood to this day, it is believed that H1504+65 is essentially a bare stellar core that might be the result of a particularly violent post-AGB very late thermal pulse which has destroyed the remaining stellar envelope containing helium and hydrogen. It could also be the result of a heavy-weight intermediate-mass star ($8\ M_\odot \leq$ M $\leq 10 M_\odot$) that has gone through carbon burning and has a O-Ne-Mg core (Werner 1991; Werner & Wolff 1999; Ritossa et al. 1999). A critical test of this idea is to measure the mass of the remnants since the offspring of such massive stars are expected to be massives as well ($\geq 1\ M_\odot$). Unfortunately, the quality of the data at hand does not allow a precise surface gravity measurement although it seems, at least for some stars, that fits with models with high surface gravity

have lines that are much too broad. However, given the low signal-to-noise ratio of the observations and the uncertainties in the broadening theory for the carbon lines, we remain cautious and will refrain from drawing any definitive conclusions at this point.

We will conclude with some thoughts on the spectral evolution of these stars. All carbon-rich white dwarfs we have found so far have effective temperatures between $\sim$ 18,000 and 24,000 K (depending on our choice of surface gravity, abundances of trace elements such as H, He and O and the amount of dereddening applied). Why do we find carbon-rich objects only in that narrow range of effective temperature ? If they are descendants of a star like H1504+65 ($T_{\rm eff} \sim 200,000$ K), why don't we see carbon/oxygen-rich white dwarfs at intermediate temperature? We believe that the simplest way to explain this is that a star like H1504+65, however it was formed, most probably still contains a tiny amount of helium which will eventually diffuse upward to form a thin layer ($\sim 10^{-15} M_*$ is enough to form a full atmosphere!) above the C-enriched and O-depleted mantle. Such stars would thus cool as normal He-rich white dwarfs until the underlying carbon convection zone develops (due to its recombination) and completely dilutes from below the tiny overlaying He layer. Hence, a star like H1504+65, showing initially a mixed C and O atmosphere, would then temporarily disguise itself as a helium-rich star before transforming itself into a carbon dominated atmosphere star at an effective temperature whose exact value is not yet known due to a current lack of proper models (hopefully around $\sim$ 24,000 K !). Furthermore, the absence of carbon-rich white dwarfs at low temperatures imply that these stars must again go through a drastic spectral change as they cool. We speculate that helium ultimately re-emerge at the surface, perhaps turning the carbon-rich white dwarfs into DQ white dwarfs belonging to the second sequence with higher carbon abundance (Dufour et al. 2005; Koester & Knist 2006). In conclusion, the surprising discovery of several white dwarfs stars with a carbon-rich atmosphere, and the explanation of their origin and evolution, represent new challenges that should ultimately deepen our understanding of stellar evolution.

Acknowledgments. This work has been partially supported by the NSF grant AST 03-07321 for work on the SDSS white dwarfs. This work was also supported in part by the NSERC (Canada).

References

Dufour, P., Bergeron, P., & Fontaine, G. 2005, ApJ, 627, 404
Fontaine, G., & Brassard, P. 2005, 14th European Workshop on White Dwarfs, 334, 49
Herwig, F., Blöcker, T., Langer, N., & Driebe, T. 1999, A&A, 349, L5
Koester, D., & Knist, S. 2006, A&A, 454, 951
Liebert, J., et al. 2003, AJ, 126, 2521
Pelletier, C., Fontaine, G., Wesemael, F., Michaud, G., & Wegner, G. 1986, ApJ, 307, 242
Ritossa, C., García-Berro, E., & Iben, I. J. 1999, ApJ, 515, 381
Thejll, P., Shipman, H. L., MacDonald, J., & Macfarland, W. M. 1990, ApJ, 361, 197
Wegner, G., & Koester, D. 1985, ApJ, 288, 746
Werner, K. 1991, A&A, 251, 147
Werner, K., & Wolff, B. 1999, A&A, 347, L9
Werner, K., Rauch, T., Barstow, M. A., & Kruk, J. W. 2004, A&A, 421, 1169

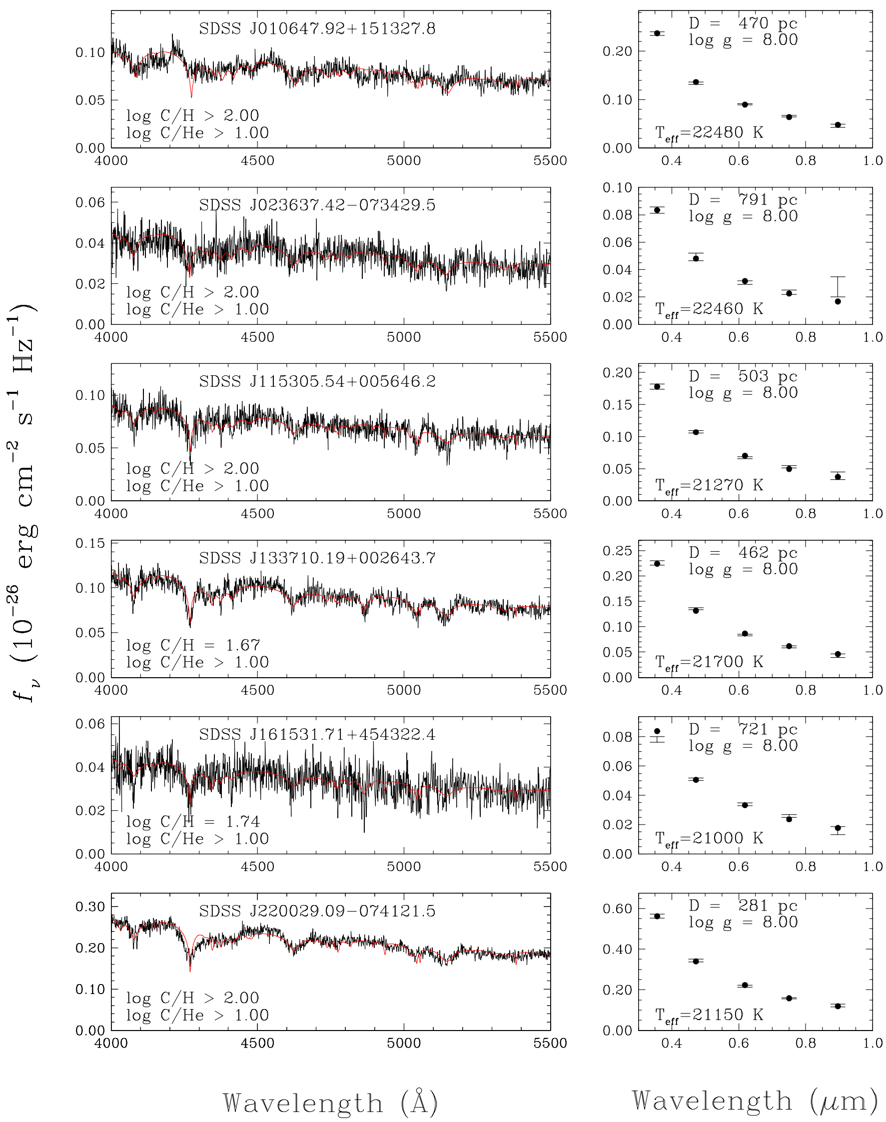

Figure 1. Fit to the optical spectra (left panel) and energy distribution (right panel) for carbon-rich white dwarfs with log g fixed at 8. The ugriz points are represented by error bar, while the average model fluxes are shown by filled circle. Hydrogen and helium abundances are constrained (or dermined in two cases) from the absence of the $H_\beta(\lambda4861)$ and HeI $\lambda4471$ lines. Photometric distances, based on the assumption that log g = 8, are indicated in each panel.